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Abstract

The issue of temporal control of motor behavior was investigated using a rhythmic tapping task. It was found that: (1) subjects are better able to tap before a beat than after a beat; (2) the variability of tapping depends on whether the subject is attempting to tap on, before, or after a beat; (3) the control of rhythmic tapping is relatively central; (4) the starting times of taps are more variable than the ending times. These results are interpreted in terms of a model by Wing (1980), and their significance for theories of timing is discussed.

The Timing of Endpoints in Movement

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Mark Wallen did the programming for this project. I wish to thank Jay McClelland and Don Norman for helpful discussion.

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The Timing of Endpoints in Movement

In moving our limbs from one position to another, it is often the case that there are temporal constraints placed upon the movement. These constraints may come from events in the environment, as when a person is catching a moving ball. Constraints can also come from the requirements of the coordination of multiple movements. For example, to throw a ball at a target, the fingers must release the ball at the proper point in time relative to the forward swing of the arm.

In many instances, it is the endpoint of the movement, or, more generally, the result of the movement that is constrained in time. In typing, endpoints have to occur in the proper sequence whereas initiations of movements are not so constrained. If fact, the order of keystroke initiation can differ in repeated typings of the same word (Gentner, Grudin, & Conway, 1980). In piano playing, the music itself imposes no restrictions on the initiation of movements. It is the timing of endpoints which is necessary to maintain the aesthetic integrity of the piece. Paillard (1946) performed an experiment in which subjects were asked to tap a finger and a toe simultaneously. It was found that simultaneity was embodied in the results of movement rather than the initiation of movement.

In the present study, endpoint timing is studied by having subjects tap with a regular metronome beat. The movement is a flexion of the index finger. Wing (1980) and Wing and Kristofferson (1973) have developed a model for a similar rhythmic tapping task in which a metronome was used only to start subjects at the desired tempo. The metronome was then turned off and subjects continued tapping. The model is composed of two parts-- an internal timekeeper that sends out regular pulses at the desired tapping rate, and the motor system which executes the desired movement. The internal timekeeper acts as a trigger, sending the pulse that starts the sequence of events leading to the movement. The motor system itself does not have a timing component. The intertick intervals of the timekeeper are assumed to form a stationary process which is independent of the time from a timekeeper pulse until the completion of the movement (i.e., the motor delay time).

Wing's model is a parsimonious account of rhythmic tapping. One purpose of the experiments reported here is to examine the extensibility of the model by investigating other aspects of rhythmic tapping. For example, consider a simple modification of the tapping task in which subjects are asked to tap before the beat rather than on the beat. Because temporal control in the Wing model resides in the timekeeper, the phase of the timekeeper must be shifted in time so that taps occur earlier. How well the subject will be able to tap to the beat, without having any taps occur after the beat, will be determined by the shape of the distribution of tapping times and the subject's error criterion. Analogous arguments hold for the case in which the subject is asked to tap after the beat. In either case, the phase shift of the timekeeper will not change the shape of the distribution of the tapping times. In particular, the variance of tapping times should be the same whether the subject is asked to tap on, before, or after the beat. This hypothesis is investigated in Experiment I.

Experiment I

Method

Subjects. Subjects were five students at UCSD, all of whom were skilled musicians, with at least five years of experience on their instrument. They were all either currently taking formal lessons or playing professionally. Four of these subjects were drummers and one was a piano player.

Apparatus. The metronome beeps were produced by a Terak computer. They were 780 Hz tones of 30 millisecond duration. The term "cycle time" will be used to describe different metronome rates. For example, a 500 millisecond cycle time implies 30 milliseconds of tone followed by 470 milliseconds of silence in an alternating sequence.

Subjects responded by tapping on a 2.54 by 6.35 mm key with a maximum downward displacement of 0.08 mm. The key made a noticeable clicking sound as it was depressed. The keypress latencies were recorded using the same clock was used to generate the metronome beats.

Procedure. Subjects tapped with the index finger of their favored hand. They held their hand just above the key in front of them, and were instructed to make brief, sharp taps.

A trial started with four metronome beats at one of four cycle times: 250, 500, 750, and 1000 milliseconds. The subject started tapping on the fifth beat and tapped 75 times with the metronome. For each of the four metronome rates there were three conditions. In the On condition, the subject was simply instructed to tap on the beat. In the Before condition, the instructions to the subject were to "tap just before the beat, as closely as possible to the beat but not on it." In the After condition, the instructions were to "tap just after the beat, as closely as possible to the beat but not on it." All other aspects of the Before condition and the After condition were identical with the On condition. No feedback was given in any condition.

The four different metronome rates were administered in a different random order for each subject. The same order was used for all three conditions. All subjects started with the On condition and were given 40 practice trials at each rate. The subjects then tapped in both the Before and After conditions, with half of the subjects starting with Before and half of the subjects starting with After. They were given forty practice trials at each rate. However, some subjects needed more practice at the faster rates. Up to 80 additional practice trials were given as needed, with the stipulation that the same number of practice trials be given in the Before and After conditions.

Results

For each subject, the deviation of keypress times from the middle of the metronome beeps was calculated. The means and standard deviations of these deviations are presented in Table 1. Each mean is based on 75 scores. One comparison of interest is between the Before condition and the After condition. For each subject, there are four metronome rates at which this comparison can be made. However, at the 250 millisecond time, the data for the After condition were unanalyzable. None of the subjects were able to tap successfully in this condition and two subjects were unable to tap in the Before condition. Therefore, the comparison was made only at the three other rates. T-tests were performed in each case between the mean for the After condition and the absolute value of the mean for the Before condition. Also, the ratios of the variances in the After and the Before condition were computed. These statistics are presented in Table 2.

Table 1

Experiment I

Means (First row) and Standard Deviations (Second row)
of Individual Subjects for the
On, Before, and After Conditions as a Function of Metronome Cycle Time

Metronome Cycle Time

	500			750			1000		
	On	Before	After	On	Before	After	On	Before	After
Subject 1	-38.0	-71.2	143.2	-20.5	-121.6	207.3	-14.6	-93.1	141.3
	30.0	35.1	59.9	16.1	40.9	42.8	41.3	59.3	41.4
Subject 2	18.3	-86.2	118.0	6.7	-111.9	129.3	3.0	-90.9	121.3
	22.7	28.0	46.4	22.4	27.9	43.6	28.1	36.2	46.5
Subject 3	1.5	-182.4	263.6	-13.7	-155.1	179.4	-23.4	-155.6	210.9
	20.2	27.3	18.5	26.1	68.9	46.6	31.1	32.9	20.6
Subject 4	-47.5	-163.6	108.9[4]	4.1	-72.4	148.0	-1.9	-68.0[3]	162.2
	20.1	50.6	131.5	46.0	31.8	64.4	50.0	64.0	55.3
Subject 5	23.6	-75.9	89.8[1]	-33.1	-94.8	103.8	-35.3	-76.0	52.6[2]
	25.3	22.7	88.8	36.3	34.9	51.4	44.6	52.3	53.5

Errors
1) 13%
2) 13%
3) 9%
4) 21%

Table 2

Experiment I

T statistics (First Row) of Comparisons between Means in the Before and After Conditions and F Statistics (Second Row) of Comparisons between Variances in the Before and After Conditions as a Function of Metronome Cycle Time

	Metronome Cycle Time		
	500	750	1000
Subject 1	9.0	12.8	5.8
	2.9	ns	0.5
Subject 2	5.1	2.9	4.5
	2.7	2.4	ns
Subject 3	23.1	2.5	12.3
	0.4	0.4	0.4
Subject 4	-3.4	9.1	9.6
	6.8	4.1	ns
Subject 5	ns	ns	-2.8
	15.3	2.2	ns

For the t-tests, the subtraction is in the order After-|Before|, so that a positive score means that the mean for Before is closer to zero than the mean for After. For the F-tests, the variance for After is in the numerator, so that numbers greater than one mean that the variance for After is greater than the variance for Before. All tests were made at the 0.01 level.

Of the 15 t-tests performed (five subjects and three cycle times), in two cases the subject tapped closer to the beat when tapping after the beat than when tapping before the beat. In two cases, the means were not significantly different, and in the remaining 11 cases subjects were better at tapping before the beat than after the beat.

It is important to take errors into consideration in this analysis. A mean close to zero may imply that the condition is easy, or it may imply that the subject has relaxed his or her criterion. In the Before condition, the subject was considered to have made an error when one of the taps came after the middle of the beat. The analogous analysis was made in the After condition. There were four occasions when a subject had an error rate higher than 3%. These cells are marked in Table 1. For subject 5, the errors render suspect the conclusion that it was easier to tap after the beat at the 1000 millisecond cycle time. Also, at the 500 time, the advantage of the Before condition over the After condition is probably unduly small. The fact that the standard deviation in the After condition is much larger than the standard deviation in the Before condition also indicates that the Before condition was easier. For subject 4, there was a significant advantage for the After condition at the 500 time. However, the error rate in the After condition was 21% compared to a zero error rate in the Before condition. Furthermore, the standard deviation is over twice as large in the After condition as in the Before condition. These considerations reinforce the conclusion that it is easier for subjects to tap before a beat than after a beat.

It is also of interest to compare the variances of the Before and After conditions with the variances in the On condition. In exactly half of the cases, the variance in the On condition was smaller than the variance in the Before or After condition. In 10 of 15 comparisons between After and On, the After variance was larger. The Before variance was less likely to be larger than the On variance; this result was obtained in 5 of 15 cases.

Discussion

The results of the first experiment demonstrate differences in the variances of different tapping conditions. In addition, it was found that it is easier for subjects to tap before the beat than after the beat. Neither result would be expected if the subject is simply shifting the phase of his timekeeper in order to tap before or after the beat.

The difference in variances between the Before condition and the After condition provides evidence against a perceptual interpretation of the fact that it is easier to tap before the beat than after the beat. According to a perceptual interpretation, the subjects may perceive that they are tapping as close to the beat in the After condition as in the Before condition, when they in fact are not. However, there would be no reason for the variances to differ.

The task used in this experiment differs from the task used by Wing in that our subjects tapped with a metronome beat whereas Wing used a metronome only for the first few beats, to set the tempo. An adaptation of Wing's model to the present task would require a mechanism in which the timekeeper could be adjusted according to the discrepancy between the tap and the metronome beat. To account for the fact that variances were higher when subjects tapped in the Before or After condition than in the On condition, it can be assumed that the correction mechanism performs worse with larger discrepancies. Since there will be larger discrepancies in the Before and After conditions than in the On condition, the tapping variance will be larger.

The observed differences between the Before and After conditions are more problematic. The nature of the task does not require that the discrepancies between the taps and the metronome beats be different in the two conditions. The difference between the conditions is that in the Before condition afference from the tap precedes afference from the metronome beat, whereas the reverse is true in the After condition. To account for the data one would have to assume that the correction mechanism performs worse when the external event precedes the tap.

At the slower rates, there is less of a tendency for the variances to differ. The variances in the After condition do not increase as rapidly over metronome rates as do the variances in the Before condition. Perhaps subjects tend to treat the After condition as a reaction time experiment at the slower metronome rates and simply respond when they hear the beat. Although this strategy is not available in the Before condition, subjects are still able to tap closer to the beat in the Before condition.

Experiment II

In the first experiment, there was an asymmetry in the task demands for the Before and After tasks. In the Before task, the metronome beep occurred just after completion of the movement, thus there was no way for the subject to use the beep as a cue. In the After task, however, the beep occurred just before the completion of the movement. Thus the subject may have been using the beep as a cue, waiting for its occurrence before tapping. Thus the tapping latency might be slowed unnecessarily, reflecting an overly cautious strategy on the part of the subject. In this case, the data would be expected to be similar to typical reaction time data.

Experiment II examined this hypothesis by removing the possibility that the beep could be used as a cue. Subjects were presented with three metronomic beeps and instructed to tap on the fourth beat. However, no beep accompanied the tap; subjects simply tapped according to their estimate of the expected position of the beep in time. On the fifth beat, a beep again occurred; this was the first of the next set of three beeps. This paradigm was used in the On, Before, and After conditions.

Another issue investigated in Experiment II is locus of cortrol. It is conceivable that the timekeeper is embodied in a peripheral motoric oscillation. Alternatively, timing might be controlled by a more central timekeeper entrained to the metronome beat. Experiment II examines this issue by pitting the frequency of the metronome against the frequency of the actual movement required. Consider, for example, the subject tapping to a metronome with a 250 millisecond cycle time. In Experiment II, the subject taps on every fourth beat, so that a tap is made once per second. In Experiment I, where the subject taps on every beat, an equivalent amount of movement is made by tapping to a metronome with a 1000 millisecond cycle time. However, an equivalent rate of the beat occurs in the condition with a 250 millisecond cycle time. If the timekeeper is peripheral, then the tapping accuracy will depend on the frequency of movement, and the 250 millisecond condition of Experiment II will be similar to the 1000 millisecond condition of Experiment I.

Method

Subjects. Three of the skilled subjects from Experiment I participated in Experiment II. Two of them were drummers and one was a piano player.

Apparatus and Procedure. The apparatus was the same as in Experiment I. The metronome again produced regular beeps, except that now every fourth beep was omitted. Thus there was silence on every fourth beat, with metronome beeps on all the other beats.

Subjects were instructed to tap only on the silent fourth beat. For example, if the cycle time of the metronome were 250 milliseconds, the subject would tap once per second. The subject tapped 75 times at each of three cycle times: 250, 500, and 750 milliseconds. This procedure was repeated under the On, Before, and After instructions, with the same randomizing of conditions as in Experiment I.

Results and Discussion

Table 3 contains the standard deviations for the On condition at the 250 millisecond cycle time, along with the standard deviations for the On condition at the 250 and 1000 times from the same subjects in Experiment I.

Table 3

Experiment II

Standard Deviations from the 250 Millisecond Cycle Time of Experiment II, the 250 Millisecond Cycle Time and the 1000 Millisecond Cycle Time of Experiment I.

	Metronome Cycle Time		
	250 (Exp. II)	250 (Exp. I)	1000 (Exp. I)
Subject 1	20.6	16.9	41.3
Subject 2	12.9	12.0	28.1
Subject 3	23.4	28.5	44.6

In columns one and three of this table, the amount of movement that the subject is making per unit time is the same. On the other hand, in columns one and two, the number of beats per unit time is the same. It is clear from this table that columns one and two are more similar to each other than are columns one and three. None of the differences between column one and two are significant, whereas all of the differences between column one and three are significant ($p<.01$). Thus, tapping accuracy seems to depend more on the number of beats than on the number of movements. This implies that the observed oscillation of the hand is being controlled by a more central timekeeper.

The means and standard deviations at all three cycle times are presented in Table 4. For subject 1, (the most skilled drummer), the results showed little change from Experiment I. At all three cycle times, the standard deviation in the After condition was larger than the standard deviation in the On condition ($F(74,74)=2.4$, 2.2, 2.3, at the 500, 750, and 1000 times respectively). At the 500 millisecond time, the standard deviation for Before was larger than the standard deviation for On ($F(74,74)=1.9$; $p<.01$). At all three cycle times, the mean in the Before condition was smaller in absolute value than the mean in the After condition ($t(148)=14.6$, 22.1, 7.2; $p<.01$). However, at the 750 millisecond time, the error rate was 79% in the Before condition. For subject 2, the standard deviations in the After condition were larger than the standard deviations in the On condition at all three cycle times ($F(74,74)=5.9$, 3.1, 10.7; $p<.01$). At the 1000 millisecond time, the standard deviation for Before was larger than the standard deviation for On ($F(74,74)=2.0$; $p<.01$). At the 750 millisecond cycle time, the mean in the Before condition was smaller in absolute value than the mean in the After condition ($t(148)=5.9$; $p<.01$). In general, the performance in the After condition was degraded for this subject relative to Experiment 1, whereas the performance in the On and Before conditions was no worse, as can be seen by inspecting the error rates and the variability. For subject 3, again the standard deviations in the After condition were significantly larger than in the On condition at all three cycle times ($F(74,74)=8.9$, 7.4, 3.5; $p<.01$). At the 750 millisecond cycle time, the variance for Before was larger than the standard deviation for On ($F(74,74)=3.1$; p,.01). In conclusion, the task in Experiment II appeared to be harder than the task in Experiment I, leading to an increased number of errors in the Before condition and both an increased number of errors and larger variability in the After condition. However, the pattern of results obtained in Experiment I still held.

Table 4

Experiment II

Means (First Row) and Standard Deviations (Second Row)
of Individual Subjects for the
On, Before, and After Conditions as a Function of Metronome Cycle Time

	Metronome Cycle Time								
	500			750			1000		
	On	Before	After	On	Before	After	On	Before	After
Subject 1	9.1	-91.1	136.0	11.5	10.2[5]	84.0	8.5	-101.4	133.3
	12.9	17.7	20.0	16.7	15.2	24.5	21.3	20.9	32.0
Subject 2	0.5	-15.6[1]	17.0[2]	10.1	-44.6	84.9[3]	-16.0	-112.2	90.9[4]
	20.6	22.9	50.2	31.7	24.5	55.6	27.7	39.2	90.5
Subject 3	5.5	-55.6	99.8	-2.2	-195.6	94.5	11.3	-264.9	178.2
	20.1	25.9	60.0	25.5	44.8	69.2	32.3	41.0	60.1

Errors
1) 24%
2) 40%
3) 9%
4) 6%
5) 79%

Experiment III

Experiments I and II demonstrated an asymmetry in subjects' ability to control the endpoints of movement. In Experiment III, the control of endpoints was further investigated by studying the relationship between the beginning and end of movement. In Wing's model, the pulse from the timekeeper precedes movement. This implies that the timing of endpoints is determined by the timing of the beginning of movement. Because successive stages in the motor execution add greater delay and greater variability to the eventual tap, it stands to reason that the earlier we measure in the sequence of events leading to the tap, the smaller the variability will be. In particular, the beginnings of the movements should be less variable than the ends of the movements. This proposition is explored by having subjects tap on a key from various distances.

Method

Subjects. Two UCSD students participated in Experiment III. Both were skilled drummers.

Apparatus and Procedure. Subjects tapped on the same key that was used in earlier experiments. Having made a tap, they moved their finger to the left until it rested upon a wooden block of the same dimensions as the metal key, placed 50, 150, or 300 mm from the key. Their tapping rate was controlled by a metronome with a cycle time of 750 milliseconds. The subjects were instructed to tap the key in synchrony with the metronome beep, return quickly to the wooden block, keep their finger on the block until it was time to make the next tap, and then make a smooth movement from the block to the key, tapping the key in synchrony with the next metronome beep. Both subjects made 75 taps on the key from each of the three distances.

Results and Discussion

The data were analyzed by using high-speed film of the tapping motions. The times of the starts of the tapping movement, as determined by the onset of the movement from the wooden block to the tapkey, and the times of the ends of the movement at the tapkey were recorded. Interresponse intervals were then calculated between successive starts and between successive ends, and the variances of these interresponse intervals were obtained. These data are presented in Table 5.

Table 5

Experiment III

Standard Deviations of the Starts and Ends of Movements as a Function of Distance from Tapkey

Distance	Subject 1 Starts	Subject 1 Ends	Subject 2 Starts	Subject 2 Ends
Long	34.8	22.0	31.0	22.4
Medium	34.6	23.6	49.5	25.5
Short	35.6	26.3	35.4	28.4

The most striking fact about the data is that the variance of the Starts is larger than the variance of the Ends. For subject 1, this result held at the long distance ($F(74,74)=2.5$; $p<.01$), the medium distance ($F(74,74)=2.1$; $p<.01$), and marginally at the short distance ($F(74,74)=1.8$; $p<.05$). For subject 2, the result held at the long distance ($F(74,74)=1.9$; $p<.01$), and the medium distance ($F(74,74)=3.8$; $p<.01$).

This result suggests that a compensation is being made during the flight of the finger from the block to the tapkey. In particular, subjects may be using temporal information in midflight. One might wish to adapt Wing's model by hypothesizing that the pulse from the timekeeper occurs when the finger is near the tapkey. There are difficulties with this interpretation, however. First, the variance of the Starts was larger than the variance of the Ends even at the 50 mm distance. Second, one must specify how the finger arrives near the key at the appropriate time.

The results can also be used to study how feedback is used to correct errors. If the subject is not exactly on the beat, then there will be a discrepancy between the sound of the metronome and the afference from the tap. The subject can then use this information to adjust the parameters of movement on following trials. If, for example, the subject is late on a tap, then the movement for the next tap can be started earlier. This leads to the prediction that the crosscorrelation of the deviation of taps from beep times and the deviation of the following start from the beep time should be negative.

However, these crosscorrelations are all positive, as indicated in Table 6. This indicates either that the use of feedback is gradual, spread over many trials, or that subjects are more likely to modulate velocity of movement than initiation of movement. Because the ends of the tapping movement are highly correlated with the starts of the movement back to the block (0.97 and 0.89 for Subjects 1 and 2 respectively), these positive correlations also suggest that the same timekeeper is responsible for timing both movements.

Table 6

Experiment III

Crosscorrelations of Discrepancies and Starts of Following Movements

	Distance		
	Long	Medium	Short
Subject 1	0.39	0.05	0.42
Subject 2	0.70	0.56	0.88

Wing's model of tapping is essentially a trigger model of tapping. The results reported in this paper pose problems for such an approach to timing. Experiments I and II indicate that if Wing's model is a correct account of the underlying mechanism of timing even when an external signal is introduced, then the process by which the timekeeper is adjusted to the signal must be complex. Experiment III demonstrates a degree of independence between the beginning and the end of movements that would not be predicted by a simple trigger model. This may indicate that a movement can be temporally monitored even after the movement has begun, with information about the relative positions of the target and the limb used to adjust velocity and direction.

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